About Depolization

Into

Shape, size distribution and composition of aerosol particles influence their scattering characteristics and thus the radiative impact. The polarization lidar technique (Schotland et al., 1971; Sassen, 1991; 2005) is a well–established method to distinguish ice clouds from water clouds and to identify layers with ice crystals in mixed–phase clouds (e.g., Ansmann et al., 2005; 2007). Freudenthaler et al. (1996) applied a scanning polarization lidar to study the evolution of contrails. The technique has been used to identify the type of polar stratospheric clouds (Toon, et al., 2000; Recihardt et al., 2000; Sassen, 2005) and volcanic ash in the troposphere and stratosphere (Winker and Osborn, 1992; Hayashida et al., 1984; Sassen et al., 2007). The polarization lidar is also well suited for aerosol profiling (McNeil and Carswell, 1975; Murayama et al., 1996; Gobbi, 1998; Cairo et al., 1999; Sassen et al., 2007) and allows us to unambiguously discriminate desert dust from other aerosols (Gobbi et al., 2000; di Sarra et al., 2001; Sakai et al., 2002; Murayama et al., 2004; Müller et al., 2003; Iwasaka et al., 2003). Based on model calculations it has been demonstrated that the spectral dependence of the dust linear depolarization ratio is sensitive to the size distribution of the nonspherical scatterers (Mishchenko and Sassen, 1998).

Lidars generate short pulses of linear polarized light. Detected backscattered signal by homogeneous shperical particles will maintain the original polarization, whereas nonspherical particleds will induse some degree of depolarization. This depolization is measured by the deopolization ration **δ**. $\delta=S_c/S_p$ is the ratio between the returned cross-polarized signal S_c and parallel-polarized signal S_p. In absense of aerosols or particles (Rayleight scattering) a depolization dm typically is of the order of 1.5%. In the case of scattering by particles, the degree of depolization depends on a large number of variables such as size and shape distributions, refractive index and phase.

Lidar studies of clouds have shown that ice crystals induce ammounts of depolarization that cary between 40% and 70%. Special cases have also been reported with depolization $\delta>=100\%$.

However, studies have shown the simple ice crystals generate a surprisingly constant amount of depolarization δ of the order of 50%, which can be decreased mainly bey the presence of liquid particles.

The measured lidar signal on both channels from range z are linked to the volume backscatter coefficient **β** of the sampled air layer by means of the lidar equation.

$$P^{\parallel,\perp}(z) = P_0 \frac{c\tau}{2} C^{\parallel,\perp} \frac{\beta^{\parallel} + \beta^{\perp}}{z^2} \exp\left[-2\int_0^z \sigma(\xi)d\xi\right], \quad (1)$$

P_0 is the transmitted pulse energy, c is the speed of light, C is the gain factor, β is the volume backscatering coef. **σ** is the extinction coef., and τ is the duration of the laser pulse. Volume backscatter coef **β** can be split into contribution from molecules and aerosols.

$$\beta^{\parallel,\perp} = \beta_a^{\parallel,\perp} + \beta_m^{\parallel,\perp}. \tag{2}$$

Atmospheric models or radiosonde vertical profiles can be used to estimate molecular backscatter. Total aerosol backscatter, in the Mie scattering regime, is related not only to the particle number density but also to the size. We can calculate the total backscatter ratio R.

$$R = \frac{\beta_m^{\parallel} + \beta_m^{\perp} + \beta_a^{\parallel} + \beta_a^{\perp}}{\beta_m^{\parallel} + \beta_m^{\perp}}. \tag{3}$$

$$R^{\perp} = \frac{\beta_m^{\perp} + \beta_a^{\perp}}{\beta_m^{\perp}}, \tag{4}$$

$$R^{\parallel} = \frac{\beta_m^{\parallel} + \beta_a^{\parallel}}{\beta_m^{\parallel}}. \tag{5}$$

The ration between parallel and perpendicular molecular backscatter δm can be assumed to be constant in the atmosphere.

Some definitions from the literature.

Symbol	Definition
δ	Volume depolarization
$R^{\perp}$	Backscatter ratio
δ_a	Aerosol depolarization
δ_T	Depolarization ratio
δ_{TA}	Aerosol depolarization

The volume linear depolarization ratio δ is not dependent on the extinction and is slightly dependent on the instrumental parametres. If the difference in efficiency between the parallel and the cross-polarized channel receiving system is not negligible an unkown gain factor C has to be estimated. K is the ration of the cross signal to the parallel signal and Ko is its value in aerosol-free region:

$$\delta = \frac{C^{\parallel} P^{\perp}}{C^{\perp} P^{\parallel}} = \frac{C^{\parallel}}{C^{\perp}} K. \qquad (6)$$

To estimate the gain factors, a calibration in the aerosol free region must be performed, which can be written as

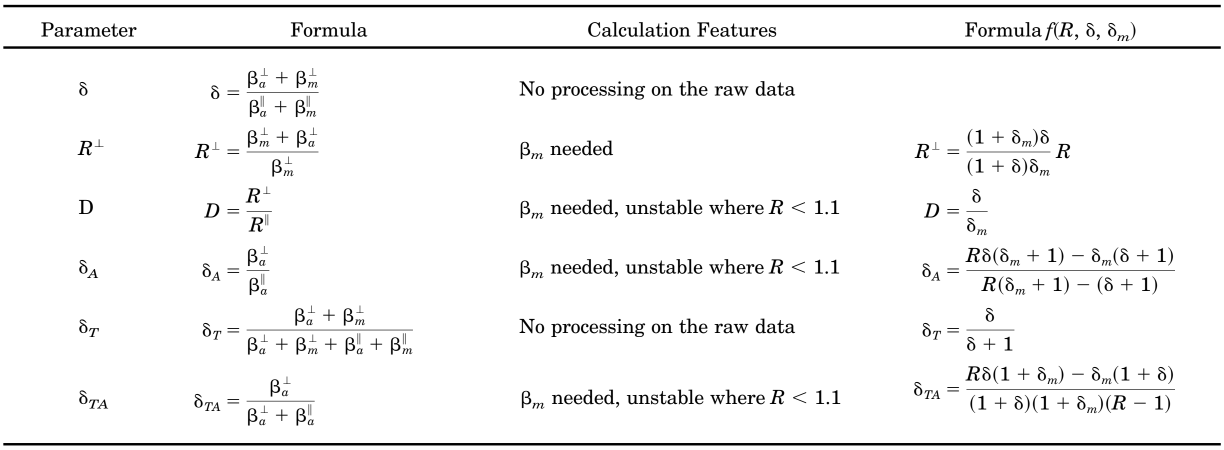
$$\delta_m = K \frac{C^{\parallel}}{C^{\perp}}, \qquad (7)$$

to have

$$\delta = \delta_m \frac{K}{K_0}, \qquad (8)$$

The ratio of the cross-backscatter coef to the total backscatter coef is expressed in terms of the raw signals:

$$\delta_T = \frac{\delta_m P^{\perp}}{K_0 P^{\parallel} + \delta_m P^{\perp}}. \qquad (9)$$



Parameter	Formula	Calculation Features	Formula $f(R, \delta, \delta_m)$
δ	$\delta = \frac{\beta_a^{\perp} + \beta_m^{\perp}}{\beta_a^{\parallel} + \beta_m^{\parallel}}$	No processing on the raw data	
$R^{\perp}$	$R^{\perp} = \frac{\beta_m^{\perp} + \beta_a^{\perp}}{\beta_m^{\perp}}$	β_m needed	$R^{\perp} = \frac{(1 + \delta_m)\delta}{(1 + \delta)\delta_m} R$
D	$D = \frac{R^{\perp}}{R^{\parallel}}$	β_m needed, unstable where $R < 1.1$	$D = \frac{\delta}{\delta_m}$
δ_A	$\delta_A = \frac{\beta_a^{\perp}}{\beta_a^{\parallel}}$	β_m needed, unstable where $R < 1.1$	$\delta_A = \frac{R\delta(\delta_m + 1) - \delta_m(\delta + 1)}{R(\delta_m + 1) - (\delta + 1)}$
δ_T	$\delta_T = \frac{\beta_a^{\perp} + \beta_m^{\perp}}{\beta_a^{\perp} + \beta_m^{\perp} + \beta_a^{\parallel} + \beta_m^{\parallel}}$	No processing on the raw data	$\delta_T = \frac{\delta}{\delta + 1}$
δ_{TA}	$\delta_{TA} = \frac{\beta_a^{\perp}}{\beta_a^{\perp} + \beta_a^{\parallel}}$	β_m needed, unstable where $R < 1.1$	$\delta_{TA} = \frac{R\delta(1 + \delta_m) - \delta_m(1 + \delta)}{(1 + \delta)(1 + \delta_m)(R - 1)}$

About depolarization callibration procedures

As we already know the total backscattered signal P(r) depending on the distance r from the lidar is described by the lidar equation

$$P = \frac{\eta\beta(r)\tau^2(r)}{r^2} \tag{1}$$

n is the system constant, β is the backscatter coef and τ2 accounts for the atmospheric tranmsittance on the way from the lidar to the scattering volume and back. For determining δ the lidar measure the atmospheric backsatter signals in two received channels, parallel and cross polarized with respect to the plane of the linear polarized output of the laser beam. The polization components are separated in the receiver (WSU) by means of polarizing beamsplitter cube (PBC).

The problem: The separation of the PBC may not perfect. (Raymetrics use the best PBC on the market today). Furthermore the polarizing PBC mign be misalinged with respect to the plane of polarization of the emitted laser beam.

The solutions:

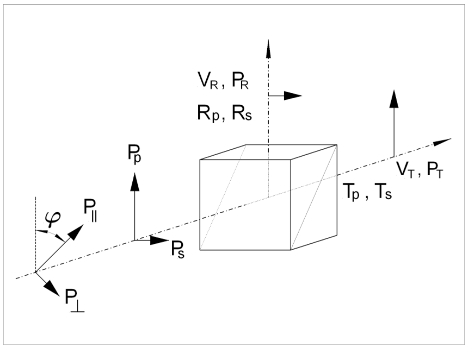


Figure 1. Signal power components in a receiver of a depolarization lidar with a polarizing beamsplitter cube with reflectivities R_p and R_s and transmittances T_p and T_s for linearly polarized light parallel (***p***) and perpendicular (***s***) to the incident plane of the polarizing beamsplitter. P_R and P_T are the measured quantities in the reflected and transmitted path, respectively, V_R and V_T are the corresponding amplification factors including the optical transmittances.

The backscatter powers before the PBC are:

$$\begin{aligned} P_\perp &= \frac{\eta_\perp\left(\beta_\perp^P + \beta_\perp^m\right)\tau^2}{r^2} \\ P_{||} &= \frac{\eta_{||}\left(\beta_{||}^p + \beta_{||}^m\right)\tau^2}{r^2} \end{aligned} \tag{2}$$

p is for particles and m is for molecules.

The total backscatter power P and the total backscatter coefficient β are the sum of both polarized components.

$$P = P_{\parallel} + P_{\perp} \tag{3}$$

The ratio of the total backscatter coef to the molecular component some times is called backscatter ratio R

$$\mathbf{R} = \frac{\beta^m + \beta^p}{\beta^m}, \tag{4}$$

and the ratio of the total cross – to the total parallel-polarized backscatter coef is called the **linear volume depolization ration δν**

$$\delta^v = \frac{\beta_{\perp}}{\beta_{\parallel}} = \frac{P_{\perp}}{P_{\parallel}}. \tag{5}$$

For the rest of the analysis we indroduce the following factors

$$\delta^*(\varphi) = \frac{P_R(\varphi)}{P_T(\varphi)}, \quad V^* = \frac{V_R}{V_T}. \tag{8}$$

δ* is the measured singal ratio, P_R and P_T are the quantiteis we actually record with our system V* is a relative amplification factor. The amplification factors V_R and V_T include the optical tranmsittances of the receivers and the electonic amplification in each channel.

Finally we get the following equation:

$$\delta^*(\varphi) = V^* \frac{\left[1+\delta^v \tan^2(\varphi)\right] R_p + \left[\tan^2(\varphi)+\delta^v\right] R_s}{\left[1+\delta^v \tan^2(\varphi)\right] T_p + \left[\tan^2(\varphi)+\delta^v\right] T_s}. \tag{9}$$

Calibration methods

In order to retreive the total backscatter power P and δ^v from the measurent P_R and P_T we need to V*, which we can get from calibratin measurements in different ways and by using eq. 9 but in the following form

$$V^* = \frac{\left[1+\delta^v \tan^2(\varphi)\right] T_p + \left[\tan^2(\varphi)+\delta^v\right] T_s}{\left[1+\delta^v \tan^2(\varphi)\right] R_p + \left[\tan^2(\varphi)+\delta^v\right] R_s} \delta^*(\varphi). \tag{10}$$

For φ=0 we get

$$V^* = \frac{\left(T_p + \delta^v T_s\right)}{\left(R_p + \delta^v R_s\right)} \delta^*\left(0°\right). \tag{11}$$

With known δ^v in some range of the lidar signal we can determine V*. The linear depolization ratio δm of air molecules is well known and thus we could use an aerosol free lidar range in the free troposhere were δ^v=δ^m.

A new method

If we calculate V* from two subsequent measuremnts at exactly 90^o diffrence we get:

$$V^* = \frac{T_p + T_s}{R_p + R_s} \sqrt{\delta^*\left(+45°\right) \cdot \delta^*\left(-45°\right)}, \tag{13}$$

This method is known as the +/-45^0 - calibration

For UNI LIDAR: $\frac{T_p + T_s}{R_p + R_s} = 0.97$

Retrieval of the linear volume depolization ratio δ^v

Once we know V* we get δ^v

$$\delta^v = \frac{P_\perp}{P_\parallel} = \frac{P_s}{P_p}, \quad \varphi = 0° . \tag{14}$$

$$\frac{P_s}{P_p} = \frac{\frac{\delta^*}{V^*} T_p - R_p}{R_s - \frac{\delta^*}{V^*} T_s} \tag{16}$$

and

$$P = P_p + P_s = \frac{V^*\left(R_s - R_p\right) P_T + \left(T_p - T_s\right) P_R}{V_R\left(T_p R_s - R_p T_s\right)} . \tag{17}$$

Usually for a polarizing beamsplitter cube we have

$$T_s = 1 - R_s, R_p = 1 - T_p, \tag{18}$$

so we have that

$$P = P_p + P_s = V^* P_T + P_R . \tag{19}$$

USA LIDAR SYSTEM SPECS:
Rs=99.5% Tp=98%

So Rs=0.995, Tp=0.98, Ts=0.005 and Rp=0.02

Retrieval of the linear particle depolization ratio δ_p

$$\delta^p = \frac{\beta_\perp^p}{\beta_\parallel^p} = \frac{\left(1+\delta^m\right)\delta^v \boldsymbol{R} - \left(1+\delta^v\right)\delta^m}{\left(1+\delta^m\right)\boldsymbol{R} - \left(1+\delta^v\right)}$$

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